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Inlet / Body Integration Preliminary Design for Supersonic Air-Breathing Missiles Using Automated Multi-Disciplinary Optimization

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Abstract

In order to reduce the design cycle time and cost and to improve the multi-disciplinary interactions at the preliminary design stage of supersonic air-breathing missiles, an automated optimization method has been developed for inlet/body integration in a concurrent engineering environment. Three disciplines of higher relevance have been considered for the *shape* optimization problem: propulsion, aerodynamics and electromagnetics. This paper describes the numerical method, which incorporates a genetic algorithm and three analysis modules into the optimization loop. The parametric model of the generic missile is presented. The optimization problem is defined and solved for a given mission and set of specifications. The problem is addressed in three phases corresponding to an increasing number of concurrent disciplines. This progression enables to emphasize the conflicting goals between the disciplines and to understand how the optimizer yields the best compromises. This preliminary study shows interesting results and strong potential for future development and industrial applications.

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1 INTRODUCTION

The main function of the inlet is to provide the engine with airflow at the necessary rate with the highest possible total pressure recovery and the lowest possible flow distortion, external drag and weight [1]. It is relatively easy to meet these objectives for a single Mach number in a uniform flow at a low angle of attack. However, it is a much more challenging task when the fixed geometry inlet must be operated in a forebody flowfield at angles of attack with sideslip and over a range of freestream Mach numbers. Moreover, missile inlets and fairings are generally responsible for a significant part of the overall lift, drag and radar signature of the vehicle. According to A. N. Thomas Jr. [1] "...the need to establish the independent missile variables as early as possible in the inlet design process cannot be overemphasized. Numerous iterations of the inlet design are to be expected because it must be carefully integrated into the engine and vehicle to achieve maximum performance". Fig. 1 gives an overview of the different fields and related constraints involved in this highly multi-disciplinary design problem. This paper presents a new approach to deal with this critical issue in a more efficient way at the preliminary design stage using traditional engineering methods combined with artificial intelligence.

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Aerospatiale Matra Missiles and Rutgers University have been working together for several years in the field of shape optimization for supersonic inlet systems [2, 3, 4]. One of the ultimate goals of this collaborative research is the development of an automated methodology for the detailed design of inlets considering the whole mission and all the necessary constraints. The detailed design requires a high level of accuracy for the geometry representation and the performance evaluation. In turn, accurate performance predictions of the exact geometry necessitate sophisticated numerical codes and refined spatial discretizations which are generally expensive in terms of computational time. It is well known that in order to solve such a multidisciplinary problem, computational power still has to increase by several orders of magnitude [5]. Other areas of necessary improvements are optimization formulation [6], advanced approximation methods [7] and multi-level physical modeling and geometry handling [8] [11]. The challenge is schematically represented in Fig. 2 [5]. The horizontal axis gives the number of concurrent disciplines. The vertical axis gives the level of numerical analysis accuracy. And the third axis gives the level of fidelity of the geometrical representation. The ultimate objective is symbolized by the red dot but as said previously, it is not yet accessible. The question is how to get there. The development strategy followed by Aerospatiale Matra Missiles and Rutgers University is threefold. The three development directions are depicted in Fig. 2 by a blue arrow. This paper presents part of the research effort which corresponds to the horizontal blue arrow. The emphasis is on integrating several disciplines into one optimization loop using approximate 2-D/3-D geometrical models and low accuracy physical analysis models.

The global problem we propose to solve in this paper is the following: find the optimum inlet design for a generic ramjet-powered missile and a set of mission specifications. The meaning of *optimum* will be defined in the subsequent sections. Because we intend to focus on the definition of the shape of the missile and inlet, three disciplines have been chosen (shaded ellipses in Fig. 1): aerodynamics, propulsion and electromagnetics. Although these disciplines do not constitute the entire space of design (structures, heat transfer, controls should also be considered) they represent the key conflicting goals. In the following sections, first the missile parametric model is defined. Second, the computational tools are described. Then the results are presented in three phases with an increasing number of concurrent disciplines and mission requirements. The difficulties and benefits of the methodology are discussed.

2 PARAMETRIC MODEL

2.1 Conceptual Model

There is one conceptual configuration for the geometric model of the generic missile. The body is made of a classical ogive/cylinder combination. The missile is equipped with 2 two-dimensional inlets and fairings and 4 fins. A view of the generic missile is given in Fig. 3. The sizes and the locations of the different components are variable parameters. To fully define one configuration, 33 parameters have to be specified. Since the investigated problem is the integration of the inlets to an existing generic missile, it has been chosen to freeze the parameters which are related to the body and fins and to keep variable the parameters which control the external and internal shape and position of the inlets and fairings.

2.2 Fixed Parameters

The fixed parameters, which define the generic missile, are shown in Fig. 4. They are defined in Table 1. The four fins have a root chord and span of 1 caliber. Their planform and position are given in Fig. 4. The ogive is of sharp parabolic type. The ramjet engine of the missile is also assumed to be fixed which has two important consequences. First, the exit location of the inlet subsonic diffuser is fixed. Second, the propulsive performance of the missile can be assessed through the aerodynamic performance of the inlets (total pressure recovery and capture area ratio).

Parameter	*Name*	*Value*
1	Missile diameter (caliber)	1 D
2	Base diameter	0.8 D
3	Missile length	14 D
4	Ogive length	2 D
5	Fin longitudinal position	13 D
6	Fin root chord	1 D
7	Fin span	1 D
8	Fin angular position	45 deg.
9	Fin leading edge sweep angle	30 deg.
10	Boattail ending position	14 D
11	Inlet diffuser exit position	11 D

Table 1. Fixed parameters

2.3 Variable Parameters

The 22 variable parameters are shown in Fig. 5. These parameters specify the external and internal shape of the inlets and fairings and their position along and around the missile. The aft parts of the inlet fairings incorporate boattails. The supersonic diffuser is made of 3 compression ramps and 3 cowl internal ramps. The external part of the cowl is made of a single ramp. The subsonic diffuser is a simple diverging duct with two slopes. The 22 design parameters defined in Fig. 5 are the variables of the automated optimization loop. Each variable parameter belongs to an interval, which is user-defined as shown in Table 2 below.

Variable	*Minimum value*	*Maximum value*
V1	90 deg.	160 deg.
V2	5 D	9 D
V3	11 D	13 D
V4	0.7 D	1.5 D
V5	0.5 D	1.3 D
V6	0.6 D	1.45 D
V7	4 D	9 D
V8	0.01 D	1 D
V9	0 deg.	10 deg.
V10	0.01 D	1 D
V11	0 deg.	20 deg.
V12	0.01 D	1 D
V13	0 deg.	30 deg.
V14	0 deg.	15 deg.
V15	0 deg.	13 deg.
V16	0 deg.	10 deg.
V17	0 deg.	10 deg.
V18	0 D	0.5 D
V19	0 D	0.5 D
V20	0 D	0.5 D
V21	0.01 D	3 D
V22	0 deg.	15 deg.

Table 2. Variable parameters

3 OPTIMIZATION LOOP

3.1 Overview

The automated optimization method is essentially a loop combining different tools. An overview of the optimization loop architecture is shown in Fig. 6. The main program is the optimizer GADO. It centralizes the information yielded by the analysis codes and directs the optimization process. The optimizer is a modified version of the genetic algorithm called GADO (acronym for Genetic Algorithm for Design Optimization) which has been developed at Rutgers University [9]. The engineering modules have been developed at Aerospatiale Matra Missiles. The modified genetic algorithm and the analysis codes are presented in the following sections.

3.2 Genetic Algorithm

Genetic Algorithms are search algorithms which mimic the behavior of natural selection to solve given problems [10]. These algorithms first generate a random collection (population) of potential solutions (individuals or candidates). Using mutations and recombinations (crossover operations), they evolve the population towards better solutions, as individuals become adapted to the problem faced. GADO belongs to this same class of optimizers. Compared to classical GAs, GADO has several improvements that have proved to increase the accuracy, speed and reliability of the search process. Further information can be found in [9].

A recent development has been added to GADO at Aerospatiale Matra Missiles, which enables to handle several objectives at the same time. Preliminary runs of the loop had shown that a single objective optimizer was not adequate to treat the multidisciplinary problem. Of course, it is possible to combine different objectives into one function to minimize (or maximize). But it introduces a comparison between measures of merit that cannot necessarily be compared physically (for example, the missile radar cross section and the inlet total pressure recovery). Thus, it was decided to treat each discipline independently. This introduces a difficulty in the ranking process within the optimizer since one design can be better than another one in one discipline and worse in the others. To overcome this issue, the Pareto ranking was used [12] [13] in which an individual is better than another one if all its objective functions are better. The result of this ranking process is the constitution of one family of designs at the end of the optimization in which no individual can be dominated by any other. The main interest of this method lies in the choice of designs which remains at the end of the optimization. The engineer has the possibility to understand afterwards the mechanisms which control the improvements in this or that discipline and to select the final design from a population of good designs.

3.3 Propulsion Code (Internal Aerodynamics)

The analysis code for propulsion performance evaluation is called OCEAS. It computes the total pressure recovery and the capture area ratio of the inlet. The code is based on 2-D analytical methods. The shocks are computed with the Rankine-Hugoniot formula. The expansion fans are modeled with a single Prandtl-Meyer wave chosen to ensure mass flow conservativity. The influence of the forebody flowfield is given as an input to the code through a table. The viscous losses in the subsonic diffuser are estimated with a one-dimensional semi-empirical code called DIFSUB associated with OCEAS. The typical CPU time needed for one performance evaluation is equal to two seconds with an SGI R10000 processor.

3.4 Aerodynamics Code (External Aerodynamics)

The aerodynamics module called AERO is a 3-D semi-empirical tool. It computes the aerodynamic characteristics of the missile airframe. The lift and drag are estimated through the normal and axial coefficients respectively. The stability of the missile can be evaluated by comparing the position of the center of pressure relative to the position of the center of gravity (static margin). The code combines analytical, semi-empirical methods and database correlations. The computational method is based on the concept of equivalent angle of attack. The vorticity effects are accounted for. The drag of the inlets and fairings is decomposed into pressure and friction drag contributions. Each contribution is evaluated with a specific relevant method. The typical CPU time for one evaluation is one second with an SGI R10000 processor.

3.5 Electromagnetics Code

The electromagnetics code called FIEL2D computes the radar signature of 2-D inlet configurations. The code solves the exact Maxwell equations with a finite element method ignoring the gradients in the third direction. The 2-D geometrical model is extracted from the general missile model and contains the inlet duct. The missile is supposed to be made of perfect electric conducting material. The analysis is limited to monostatic scattering. The measure of merit used to characterize the radar signature is the average for several frequencies of the maximum computed radar cross section over a range of monostatic angles for both the transverse electric (TE) and transverse magnetic (TM) polarizations. The CPU cost for one frequency and one angle is less than one second with an SGI R10000 processor.

3.6 Summary

To summarize, there is a total of 6 measures of merit (Table 3) that can be computed for each missile configuration with the three analysis codes: the total pressure recovery, the capture area ratio, the normal force coefficient, the axial force coefficient, the static margin, and the radar signature. The notations corresponding to Table 3 are given at the end of the paper. Each of these can be treated in the optimization process either as a constraint (a certain level must be obtained) or as an objective (minimum or maximum search) or it can be deactivated (the discipline is not taken into account). The fitness function (Fig. 6) is a vector of the penalty function and several objective functions (depending on the number of disciplines involved). The penalty function is proportional to geometrical and physical constraint violations. The objective functions which will be the focus of this study are: maximize the inlet total pressure recovery, minimize the missile drag and minimize the inlet radar cross section.

Discipline	*Symbol*
Propulsion	$\eta_{02} = Pt_2 / Pt_0$
	$\varepsilon = A_0 / A_C$
Aerodynamics	$C_N = N / (\rho_0 V_0^2 S_R / 2)$
	$C_A = D / (\rho_0 V_0^2 S_R / 2)$
	$\Delta s = Xcp - Xcg$
Electromagnetics	$\sigma = \lim_{R\to\infty} 4\pi R^2 \lvert E_S \rvert^2 / \lvert E_0 \rvert^2$

Table 3. Measures of merit

4 RESULTS

4.1 Mission Specifications

The generic missile flight mission has been modeled with 5 flight conditions presented in Fig. 7. These conditions are representative of a typical ramjet-powered missile mission with an acceleration phase (between t1 and t3), a cruise phase (between t3 and t4) and a maneuver phase (between t4 and t5). These conditions are used for the propulsion and aerodynamic evaluations. The radar signature is estimated for the frequency and bearing domains given in Table 4 below.

Parameter	*Range*
Frequency	2 - 6 GHz
Bearing	- 45, + 45 deg.

Table 4. Radar signature analysis domain

The general objective of the study is to integrate two square inlets to the generic missile in the best possible way in order to maximize the total pressure recovery and minimize the drag and radar signature. The optimum designs must also satisfy constraints on the inlet capture area ratio, the lift of the missile and its stability. To understand how the design is optimized, the study is performed in three phases (called cases 1, 2 and 3). Case 1 corresponds to the optimization of the inlet from the propulsion point of view. The aerodynamics and the radar signature of the missile are not taken into account (the disciplines are deactivated). This case should yield the best possible propulsive performance but the multi-disciplinary integration should be poor. The second case corresponds to the integration of the inlet to the missile considering both propulsion and aerodynamics. The radar signature is not taken into account. The result should be a lower performance in propulsion but a lower drag as well. Finally, the third case brings together the three disciplines and should give the best compromise. A summary of the three test cases is given in Table 5 below. The constrained measures of merit must satisfy inequalities that will be specified in the description of each test case.

Case	*Discipline(s)*	*Objective(s)*	*Constraint(s)*
1	Propulsion	*maximize* η_{02}	ε
2	Propulsion	*maximize* η_{02}	ε
	Aerodynamics	*minimize* C_A	Δs, C_N
3	Propulsion	*maximize* η_{02}	ε
	Aerodynamics	*minimize* C_A	Δs , C_N
	Electromagnetics	*minimize* σ	

Table 5. Description of the three test cases

4.2 Case 1

The objective of this test case is to obtain the best possible inlet from the propulsion point of view. The aerodynamics and electromagnetics codes are deactivated.

The two measures of merit associated with propulsion are the inlet total pressure recovery and capture area ratio. The single objective is to maximize the total pressure recovery over the whole mission. The single constraint is that the capture area ratio must be greater than 0.8 for each flight condition.

The shape of the optimized inlet is given in Fig. 8 (dotted lines). The geometry is characterized by its large dimensions. The length and the width are almost maximum to allow for the highest possible amount of compression in the supersonic diffuser and a gentle subsonic diffusion. The optimizer has chosen a design Mach number of 2.6 which gives good performances for cruise and maneuver. The resulting missile is shown in Fig. 9 (top figure). The inlets are located under the missile body to benefit from the inflow pre-compression when at positive angles of attack. The resulting performances are shown in Fig. 10. The top left plot shows the total pressure recovery for each flight condition. The bottom left plot gives the capture area ratio for each flight condition. It can be noted that the constraint is satisfied. The other measures of merit have been computed afterwards and are shown in the four remaining plots of Fig. 10. It can be seen that the resulting missile is unstable and would not have been selected in a multi-disciplinary optimization. Also the average radar signature is quite high.

4.3 Case 2

The objective of this test case is to understand how the previous design changes when external aerodynamics comes into consideration. The electromagnetic contribution is deactivated.

The two objectives are to maximize the inlet total pressure recovery and to minimize the missile drag over the whole mission. The inlet capture area ratio is constrained as before and the normal force coefficient must be higher than the threshold values given in Table 6. The stability of the missile is constrained through the static margin which must be positive and smaller than 1 D for each flight condition of the mission.

Flight condition	*1*	*2*	*3*	*4*	*5*
Minimum C_N	0.	1.	0.8	0.	2.

Table 6. Constraints on normal force coefficient

One optimum inlet has been chosen in the population of the best designs generated by the optimizer. The profile of the inlet is shown in Fig. 8. The design is obviously smaller than the one of case 1 which is logical. Both the length and capture area have been reduced in order to decrease both the pressure and friction drag. Also the design Mach number is smaller (2.5) which helps to reduce the spillage drag contribution during the acceleration phase. The external cowl angle is smaller too. The resulting missile is sketched in Fig. 9. The performances of this second missile are compared to the previous ones in Fig. 10. This second missile is stable (top right plot in Fig. 10) and has a low axial force coefficient (top middle plot). The radar signature has been computed afterwards and is of the same level as the one of case 1.

4.4 Case 3

The last case incorporates the three engineering disciplines. The objective is to understand how the radar signature consideration affects the aerodynamic design.

The three objectives are to maximize the inlet total pressure recovery, to minimize the missile drag and to minimize the inlet radar signature. The constrained measures of merit are the same as in the previous case and the specified levels are unchanged.

Among the best design family, one individual has been chosen as a reasonable compromise. The inlet geometry is shown in Fig. 8. The capture area of the inlet has been further reduced in order to make the size of the cavity opening smaller in comparison to the considered wave lengths. In order to satisfy the lift constraint, the length of the inlets had to be increased even though it penalized the friction drag contribution. The smaller capture height prevents from having a lot of compression in the supersonic diffuser which explains the loss in propulsive performance.

5 CONCLUSION

An innovative preliminary design method has been developed for the integration of inlets to supersonic air-breathing missiles. This automated method enables to take into account several essential engineering disciplines at the very beginning of the design phase in a fully concurrent way. This study has shown the strong potential of such an approach and the necessity to use a multi-objective optimizer. More work remains to be done in the development concerning the improvement of the analysis codes. In particular, 3-D extensions of the propulsion and radar signature codes would be a significant improvement.

Acknowledgments

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Notations

η_{02}	Inlet total pressure recovery
ε	Inlet capture area ratio
C_N	Missile normal force coefficient
C_A	Missile axial force coefficient
Δs	Static margin
σ	Inlet radar cross section
Pt	Total pressure
A	Stream tube cross section
N	Normal force
D	Axial force
V	Velocity
ρ	Air density
S_R	Reference cross section

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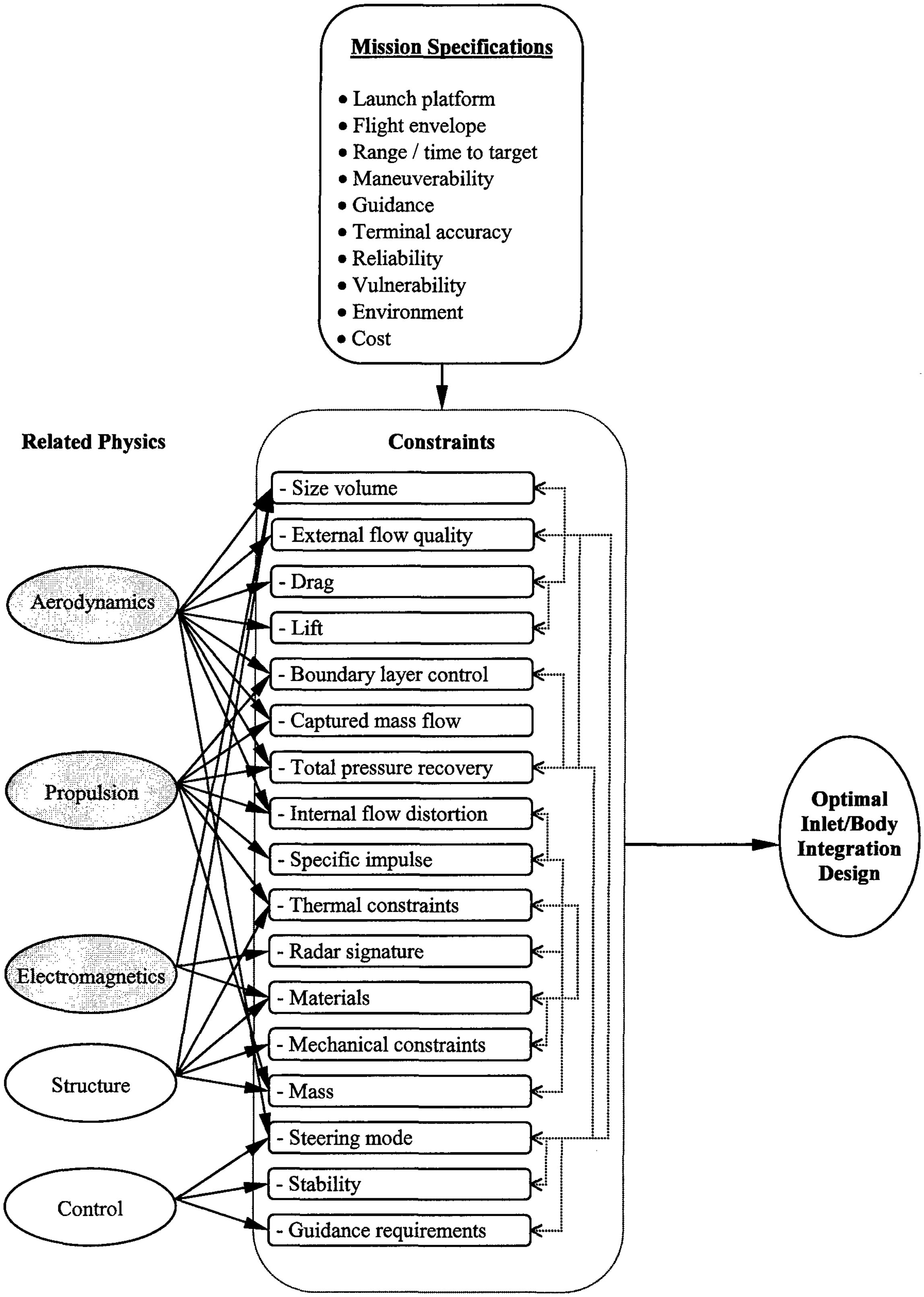

Figure 1. Inlet / missile integration design

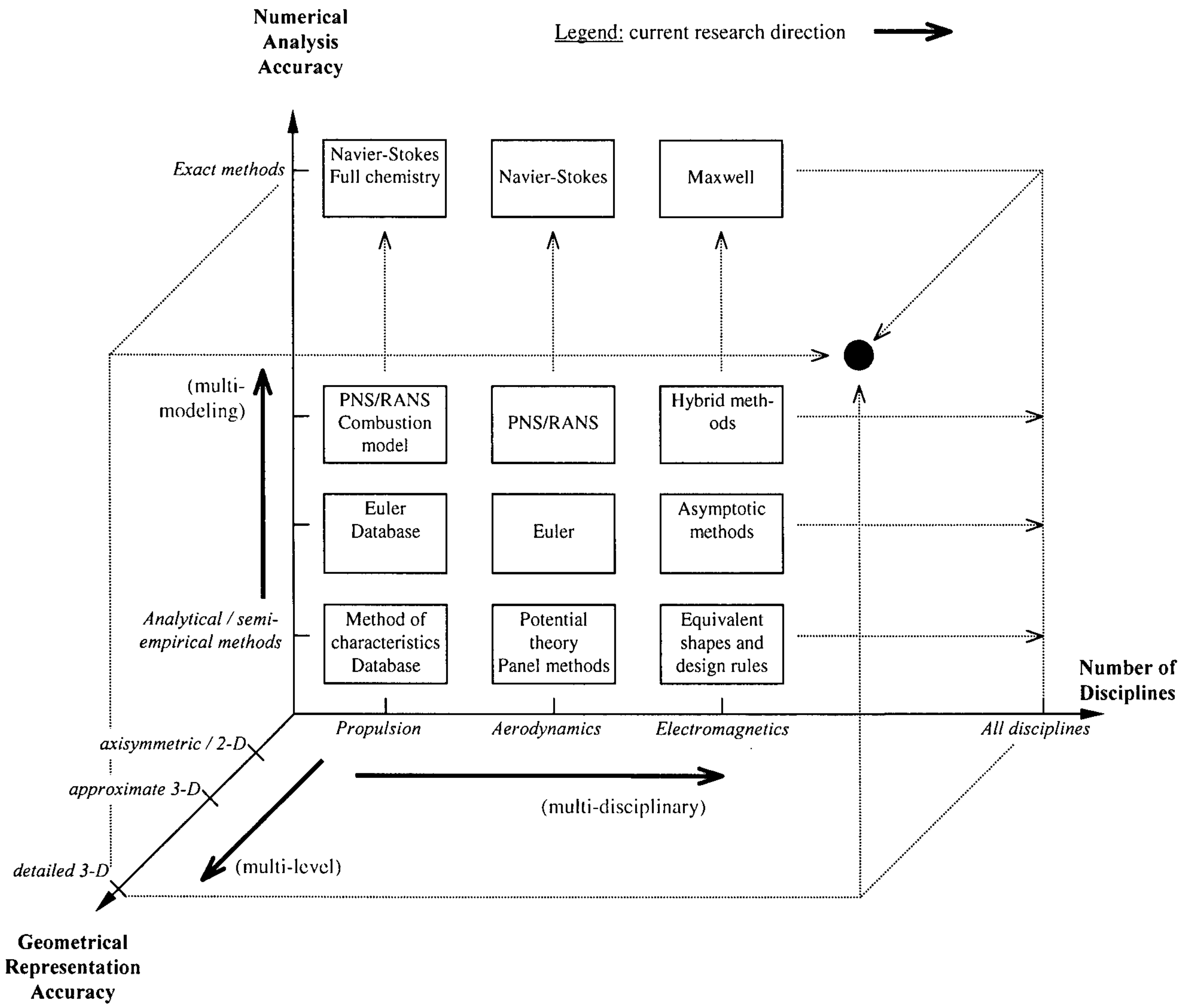

Figure 2. Development directions in the research space for inlet / missile integration optimization

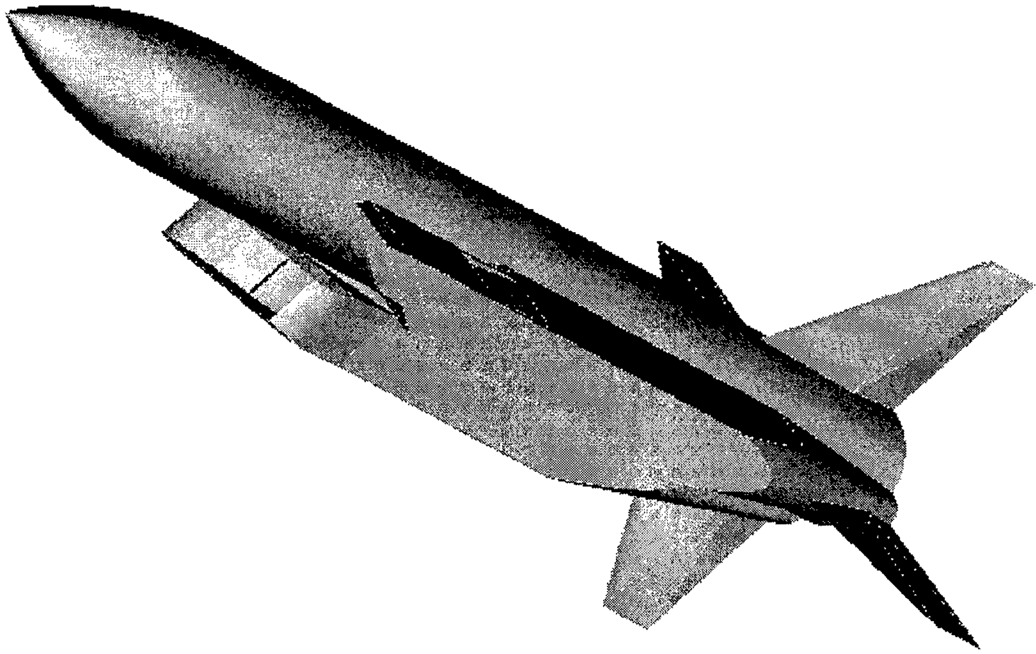

Figure 3. Generic supersonic air-breathing missile

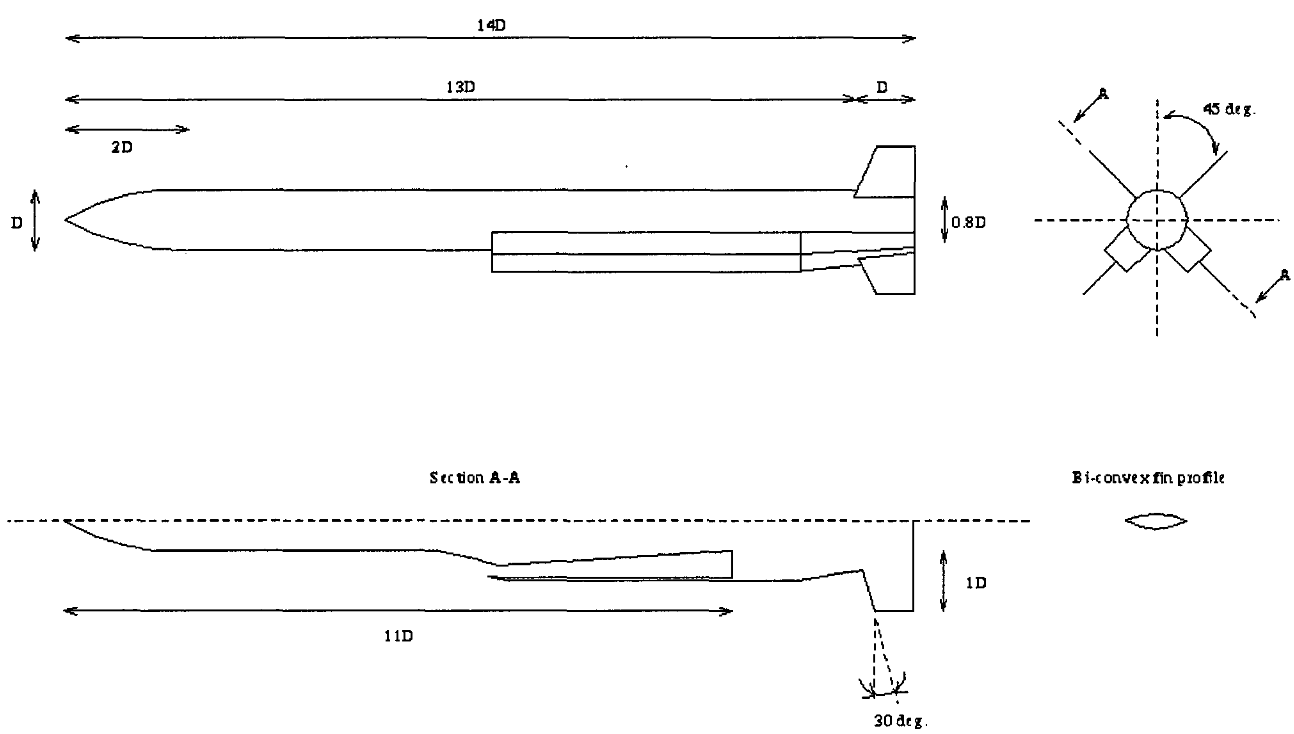

Figure 4. Missile parametric model – Fixed parameters

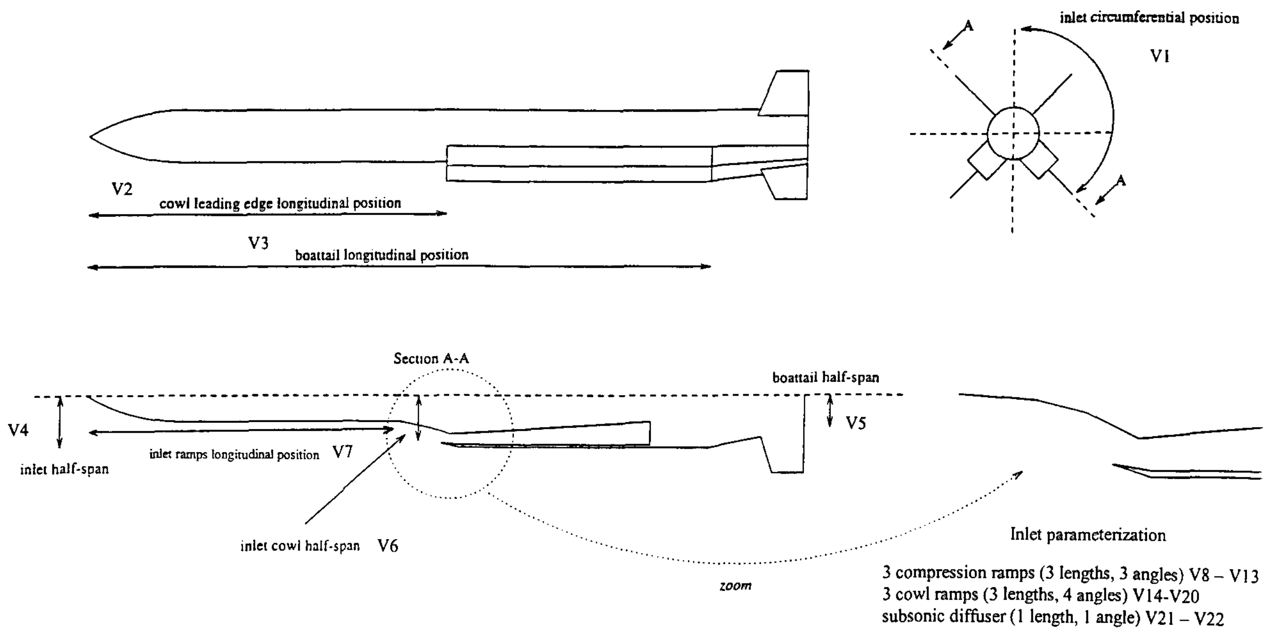

Figure 5. Missile parametric model – Variable parameters

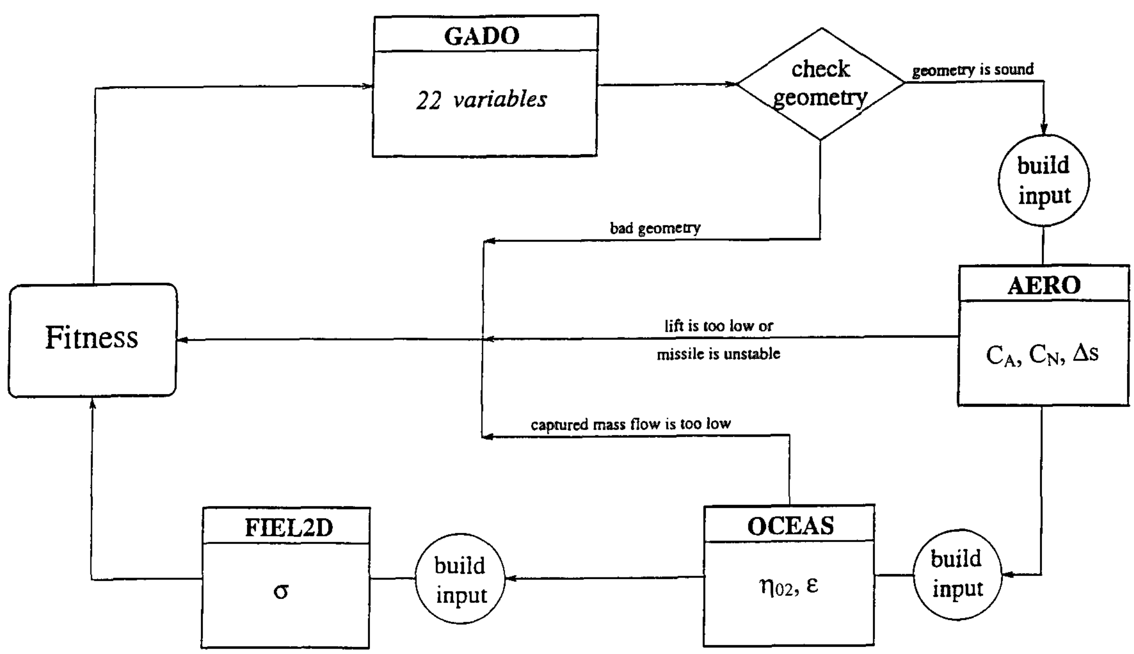

Figure 6. Optimization loop architecture

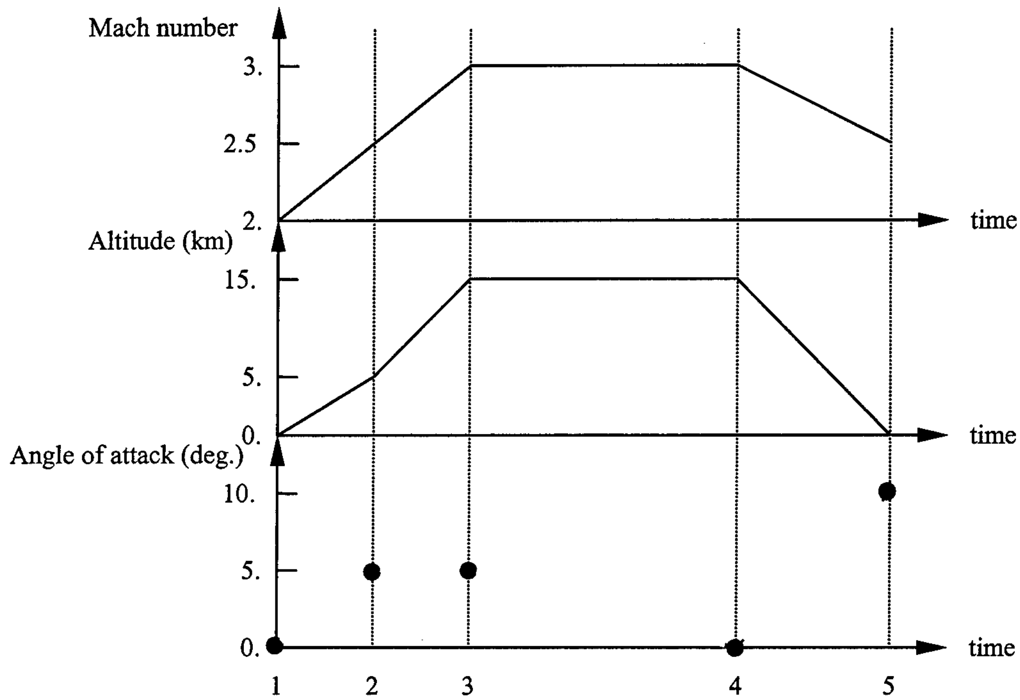

Figure 7. Mission trajectory

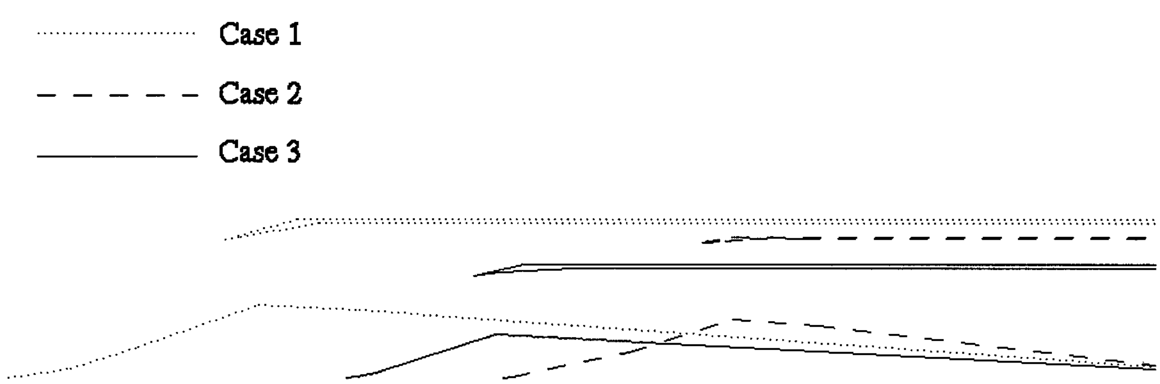

Figure 8. Shape of optimized inlets

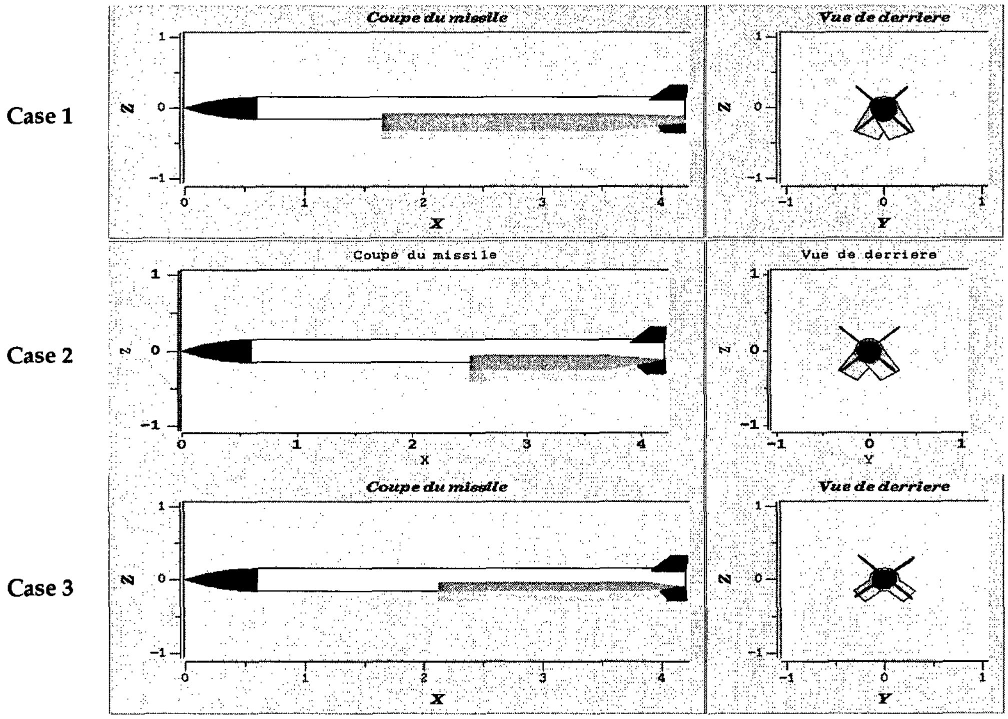

Figure 9. Optimized missile designs

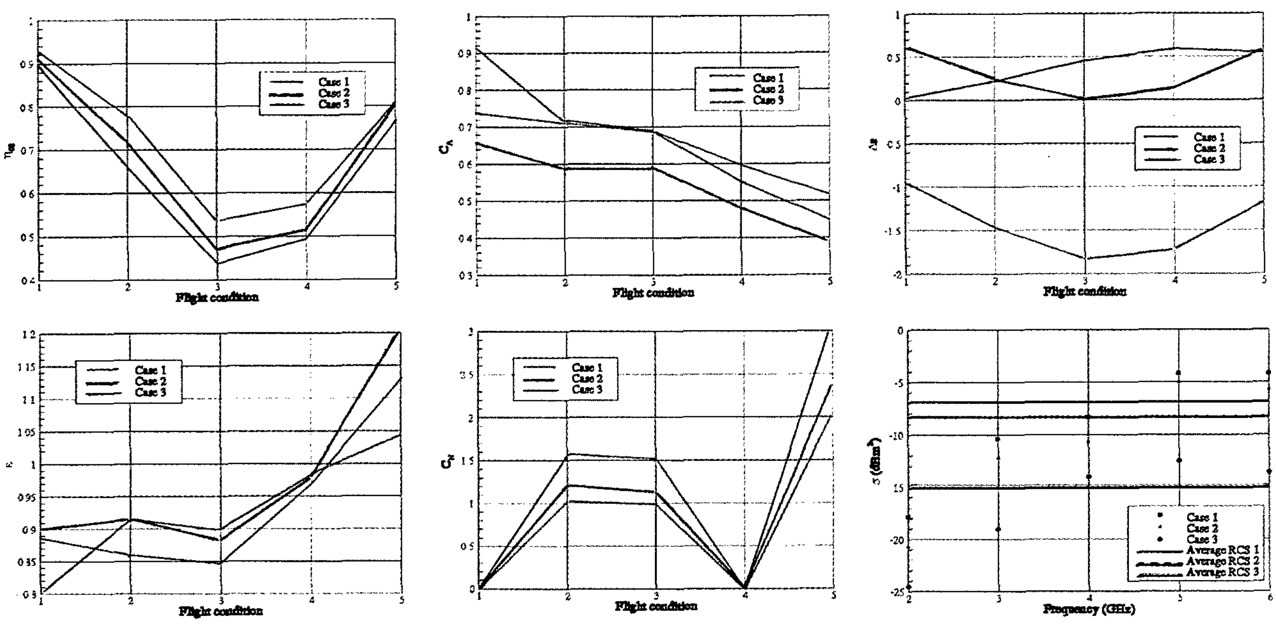

Figure 10. Performances